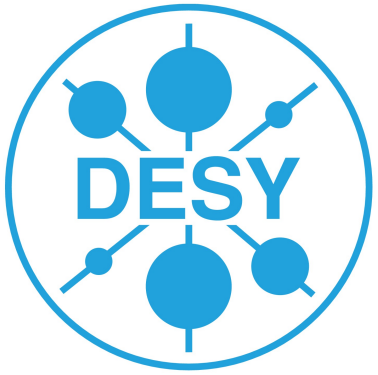
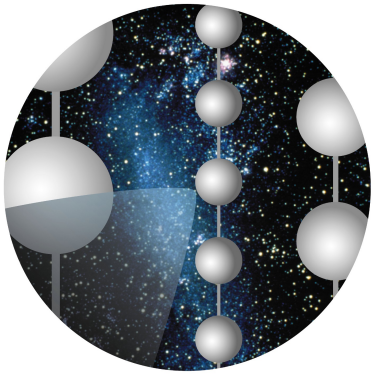




Reconstruction and Identification of Neutrino-Induced Particle Showers in IceCube

Eike Middell
DESY Zeuthen

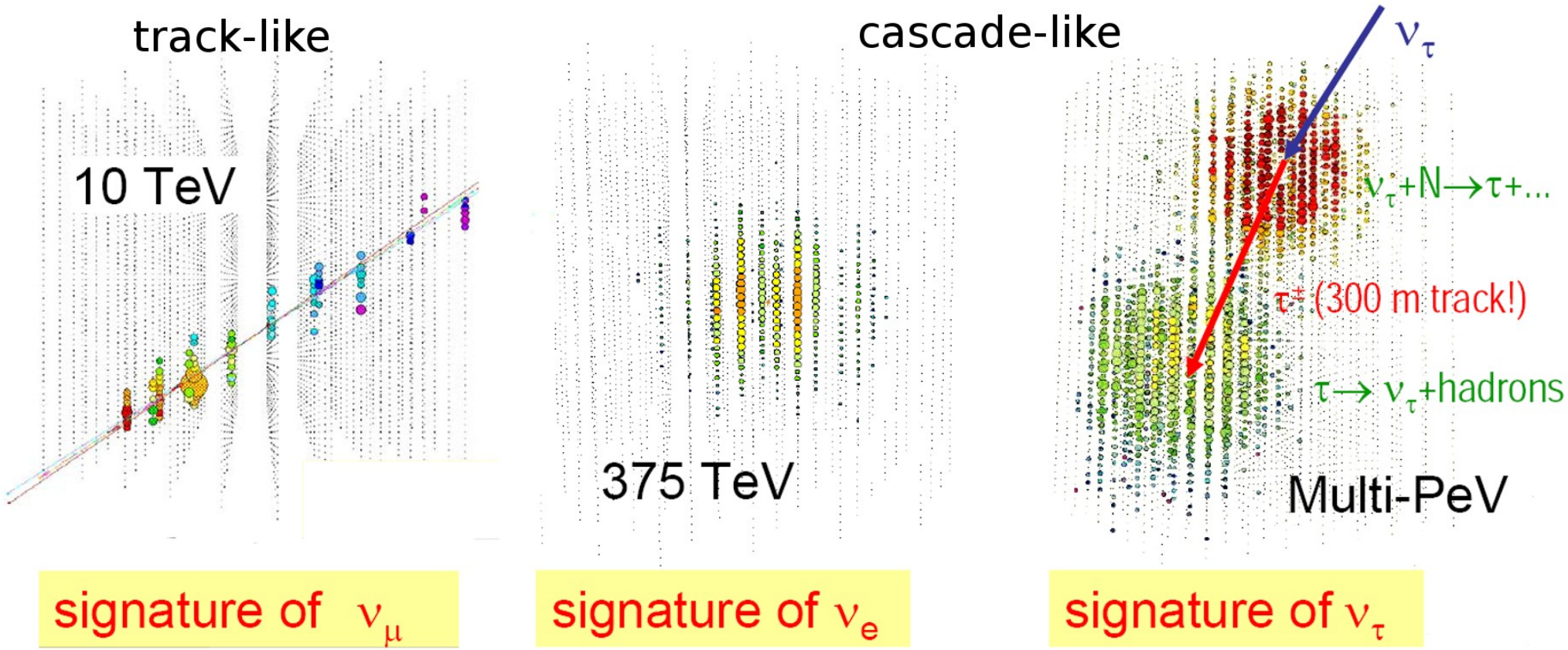
VLVνT 2011 – Erlangen
13.10.2011

Outline

- Event signatures
- IceCube and the optical properties of South Pole ice
- Simple reconstructions
- Likelihood reconstructions
- Additional methods for shower/muon separation
- Recent results with IC40

Event Signatures

- depending on the incident primary two main signatures: track-like and cascade-like
- reconstruction algorithms derive event properties under one of these two hypotheses

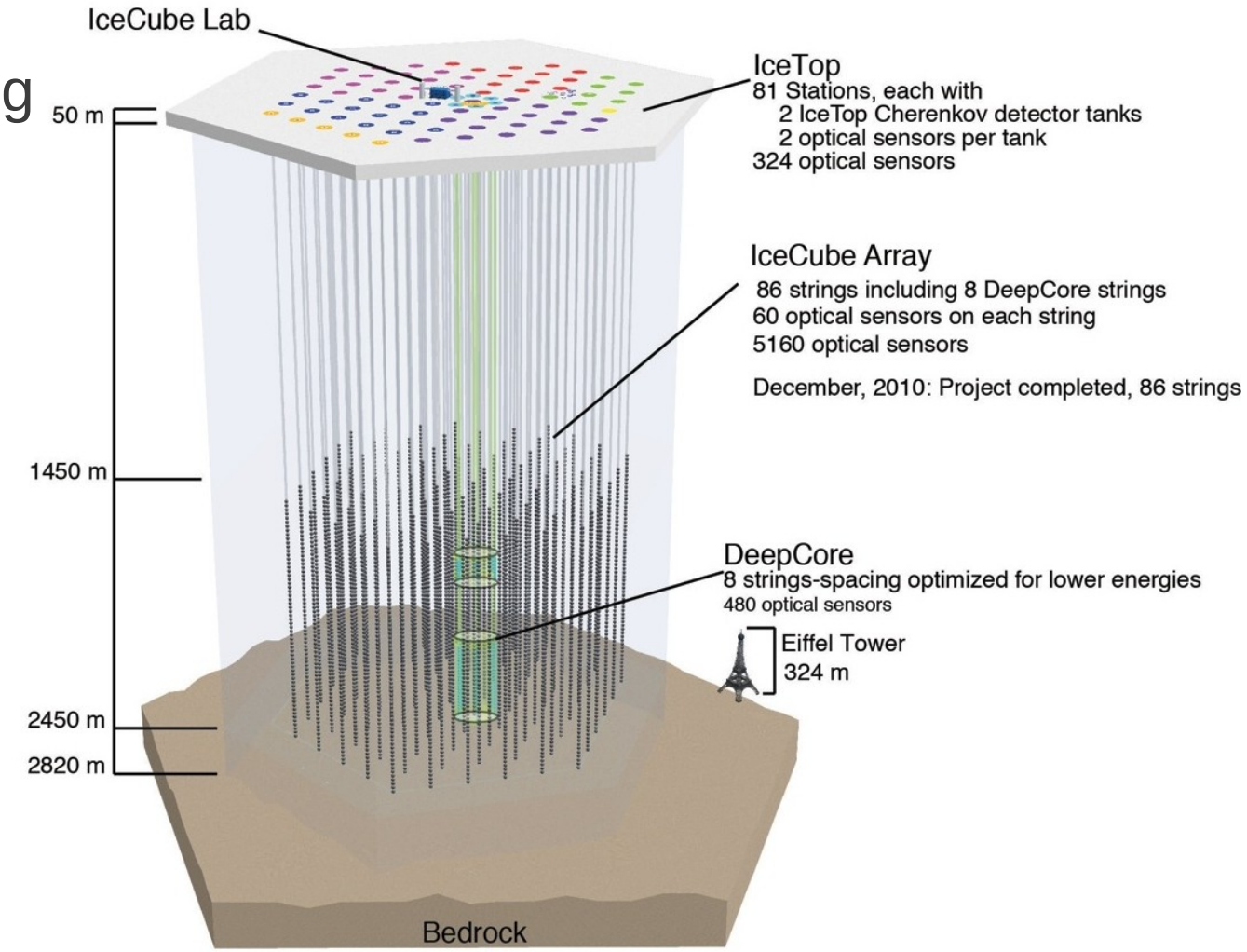


IceCube Properties

- optical properties of South Pole ice change with depth
- avg. scattering length
  $\lambda_e \approx 30$ m
- horizontal string spacing determines shower energy threshold:

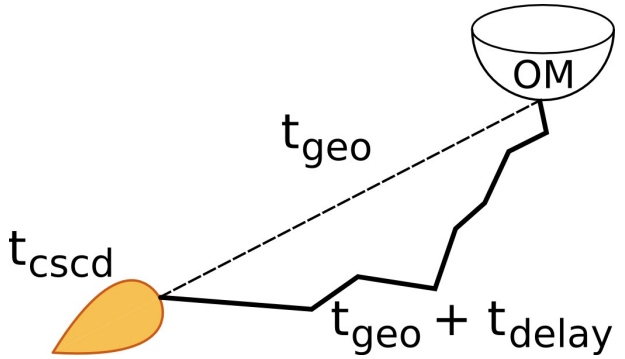
  IceCube: ~1 TeV

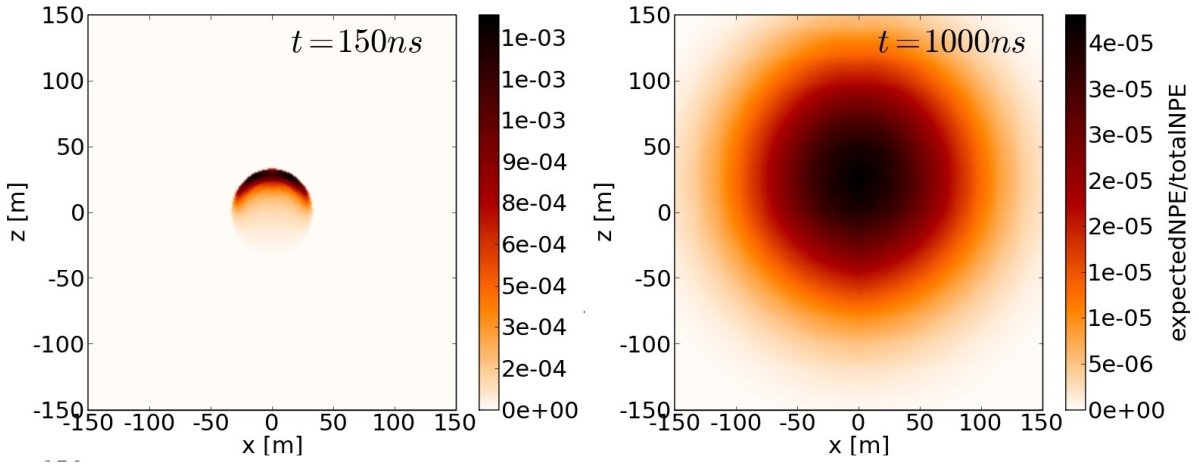
  DeepCore: ~100 GeV



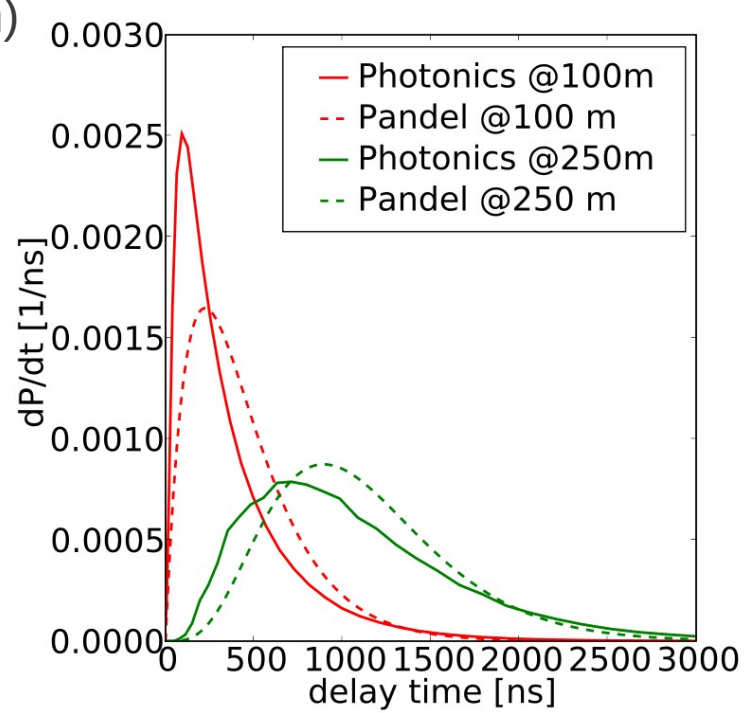
Particle Showers in IceCube

- photons arrive delayed up to µs
- anisotropic emission profile strongly washed out
- elaborate simulation of light propagation either
  - event by event → PPC (see talk #100 D.Chirkin)
  - tables → Photonics (astro-ph/0702108)



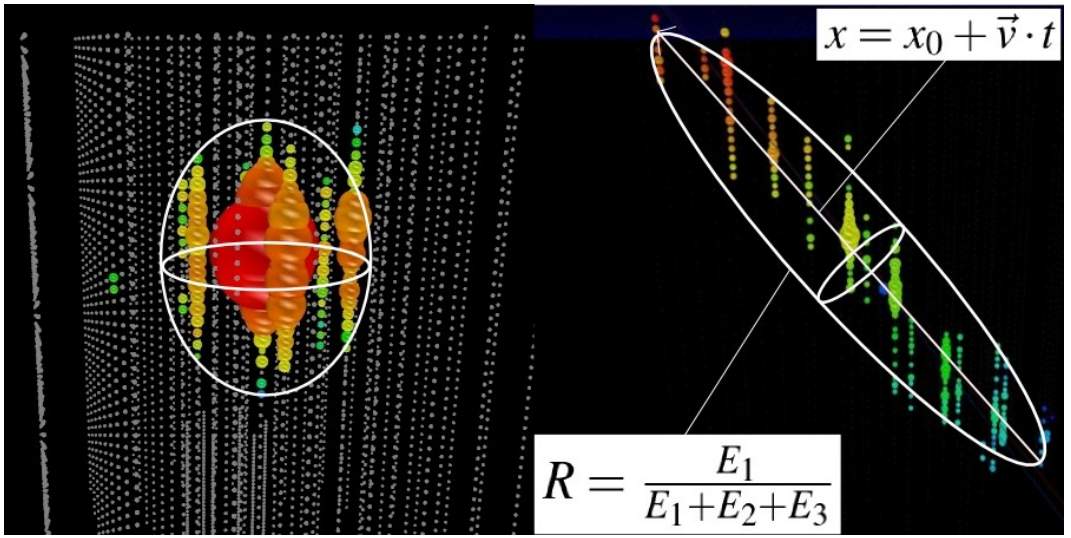


expected light distribution after 150ns and 1000ns



Simple Reconstructions / Shape Parameters

analogy to classical mechanics
- total recorded charge ↔ mass
- center of gravity → vertex
- tensor of inertia eigenvalue ratio
  R → 1/3 for spherical events



- straight line fit $\vec{x} = \vec{x}_0 + t \cdot \vec{v}$ yields velocity parameter how fast the hit pattern evolves

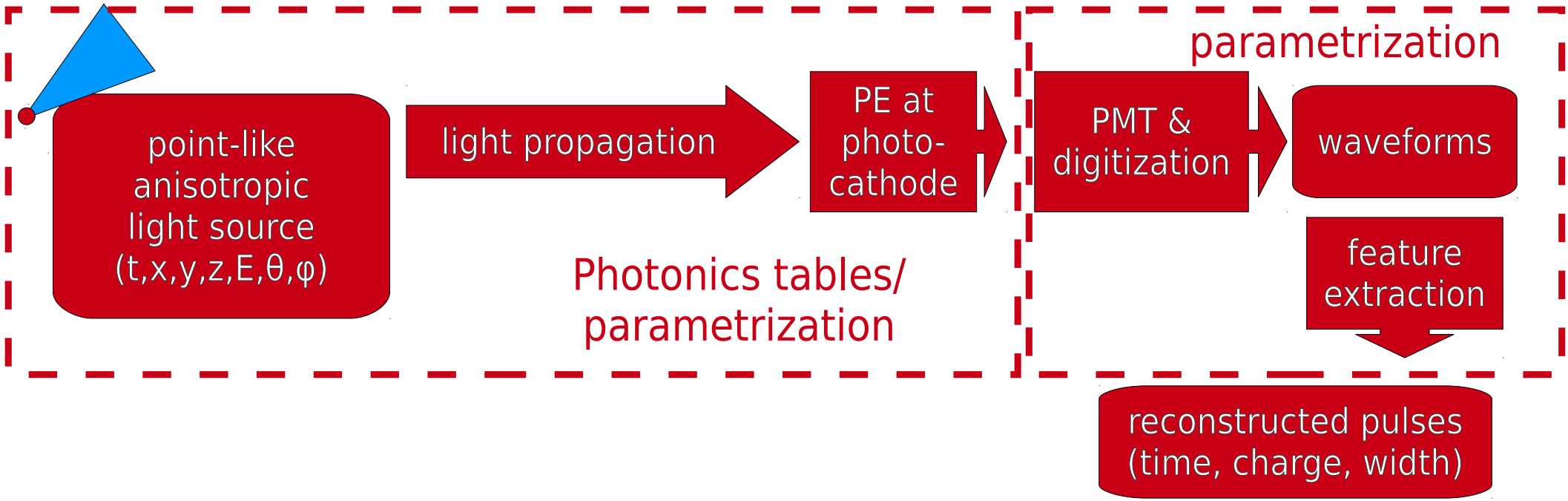
- time-depth correlation to reject strongly up- and down-going hit patterns

$$cor(t,z) = \frac{\sum_{i=0}^{N} (t_i - \langle t \rangle)(z_i - \langle z \rangle)}{N \sigma_t \sigma_z}$$

- fast to compute
- first guess algorithms → seeds
- used in cascade online filter
  e.g. IC59
  trigger: 1.6 kHz → Level 1: 24 Hz
  78% Efficiency (E^{-2} ν_e)

Likelihood Reconstructions

- need a probabilistic description of the measurement
- reconstructed pulses contain whole available information of the event
- estimate the set of shower parameters that fit best to the recorded event
- maximum likelihood value is quality parameter for the hypothesis



Likelihood Implementations

Timing only

- combine for each DOM o at position (x,y,z) the probability p to have a hit at time t

$$L = \prod_{\text{hit DOMs } o} p(t_o, x_o, y_o, z_o)$$

- isotropic light source
- homogeneous opt. properties
- analytical description of arrival time distribution (Pandel)

Timing & Amplitude

- Poisson process in each time interval (waveform bin, reconstructed pulse)
- tables provide expected charge and arrival time distribution
- in DOM o, time interval / pulse i: compare charge n_{oi} to prediction μ_{oi}

$$L = \prod_{\substack{\text{hit DOMs} \\ o}} \prod_{\substack{\text{Pulse} \\ i}} \frac{\mu_{oi}^{n_{oi}}}{n_{oi}!} \exp(-\mu_{oi}) \prod_{\substack{\text{unhit DOMs} \\ o}} \exp(-\mu_o)$$

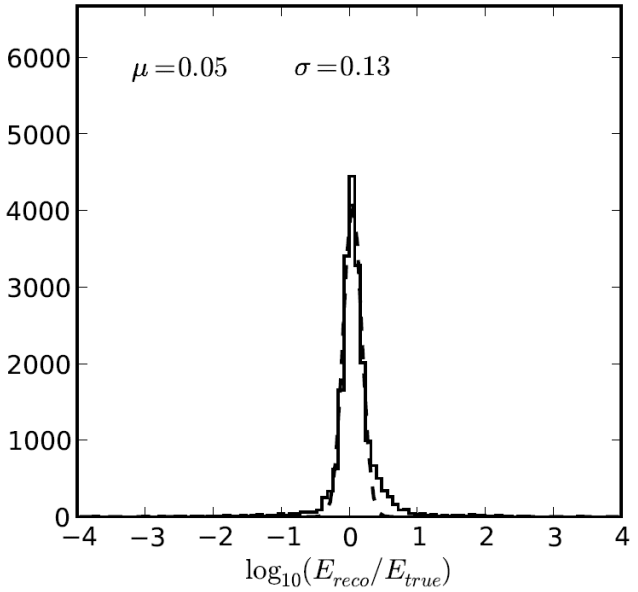
energy only

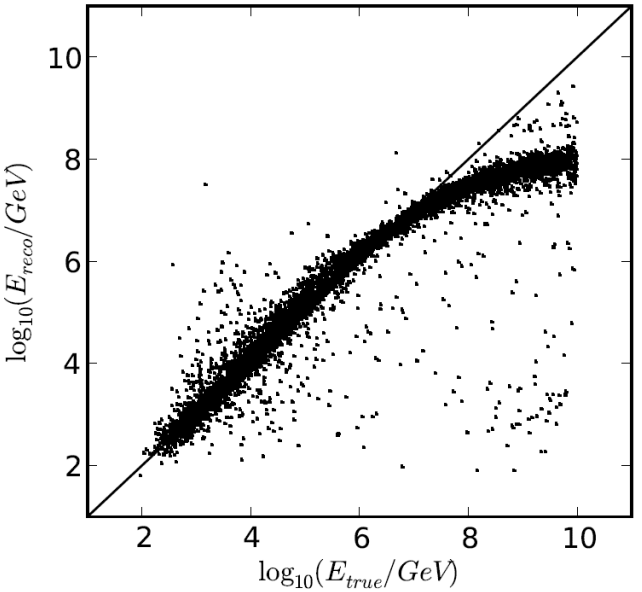
- vertex fixed
- energy estimator that considers depth dependent ice properties

vertex,time,energy,direction

- 7 dim. Parameter space
- iterative minimization to escape local minima
- slow but performs best

Performance





- simulated ν_e E^{-2} IC40 dataset
- contained events
- energy resolution: σ(log E)=0.13
- vertex resolution:

  σ(x) = < 10m

above 10PeV:

- saturation effects & point-like reconstruction hypothesis not longer applicable

direction:

- hints in MC for a limited angular resolution but confirmation with real data is still missing

further improvements under way:

- spline-based interpolation of Photonics tables: analytical gradients, potentially smoother likelihood landscape

Muon Reconstructions

Zenith Angle:

- reconstructions with muon hypotheses tend to interpret particle showers as a horizontal muons
- provides some separation from the mostly downwards reconstructed atm. muons

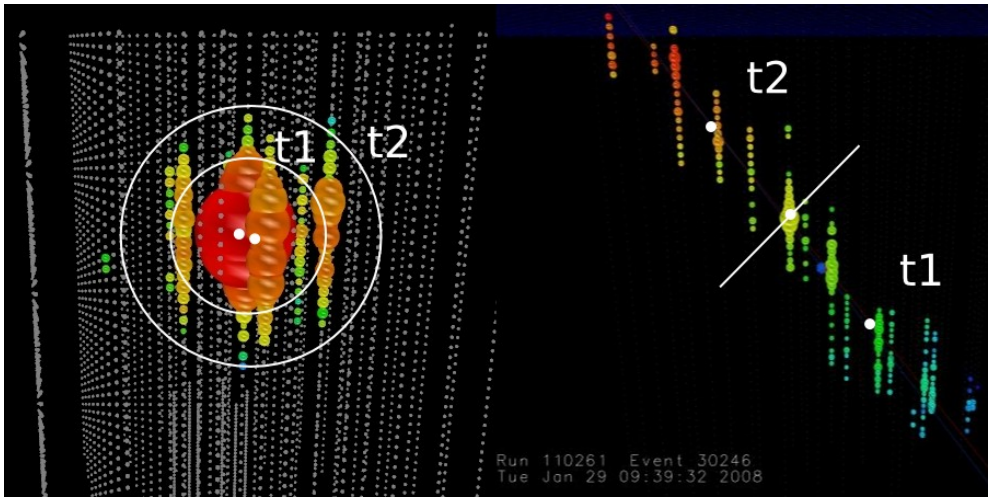
Hypothesis Test:

- likelihood ratio of reconstructions with muon and shower hypotheses
- current work: Millipede algorithm (see #102 D.Boersma)
  - fits individual energy losses on muon tracks
  - eventually will allow to test
    single cascade vs. muon + bremsstrahlung cascade hypotheses

Reconstruction Stability & Coincident Events

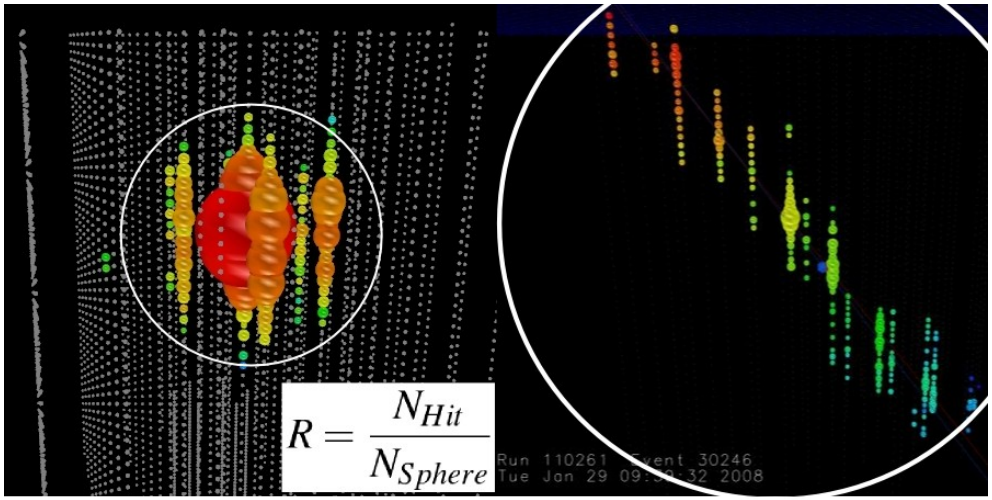
split reconstructions:

- splitting hit pattern by time into two halfes selects:
  - showers: core/corona
  - tracks: different track segments
  - coincident muons: different tracks
- reconstruct both individually and compare vertex locations



Fill Ratio:

- construct a sphere around the reconstructed vertex
- ratio of hit DOMs to all DOMs inside the sphere allows to reject non-spherical events



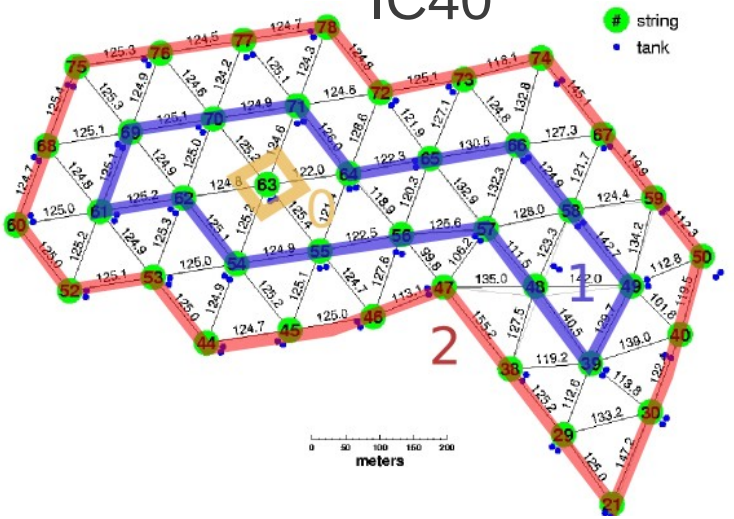
Vetoing / Containment

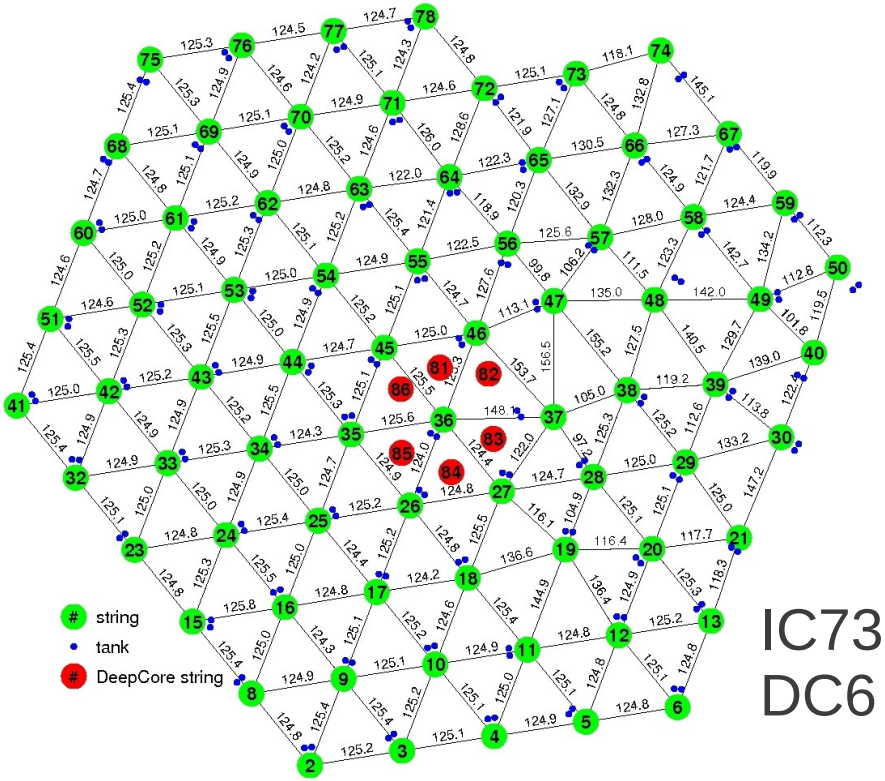
- energy/distance degeneracy for interactions outside the detector
- reject atm. μ when they enter the detector

- early IceCube configurations provided only limited possibility to define veto regions
- simple vetos:
  - first hit/DOM with max charge may not occur on outer layer
  - reconstructed vertex in fiducial volume

- beginning with IC79 one can utilize more elaborated veto criteria,
  e.g. testing if hits in Deep Core are causally connected to hits in veto region

IC40





IC73+
DC6

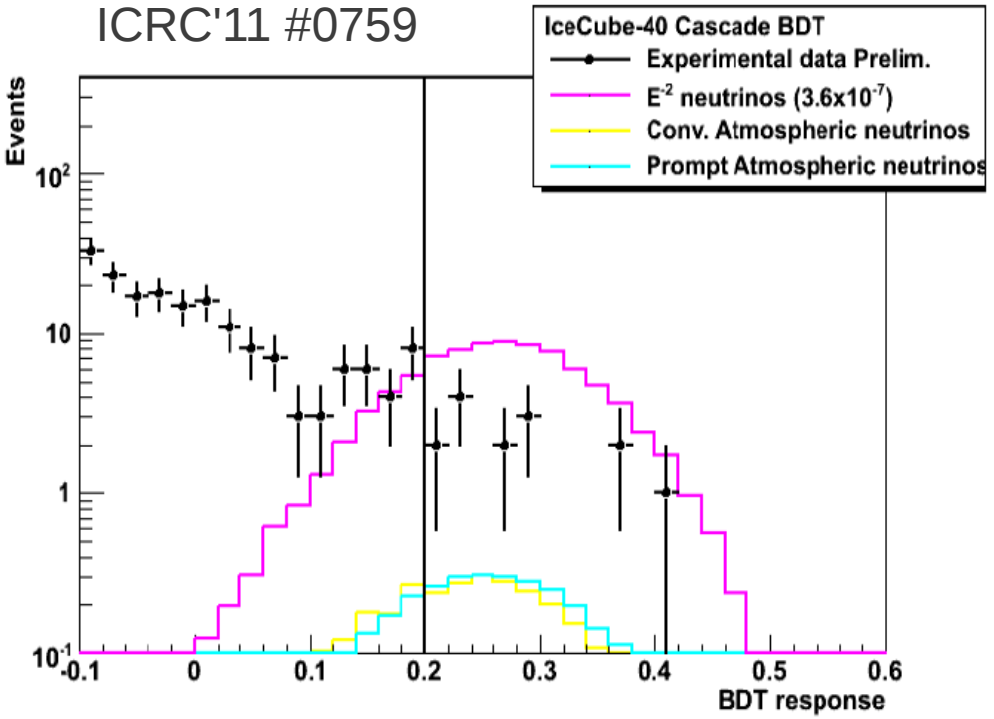
Shower Identification with IC40

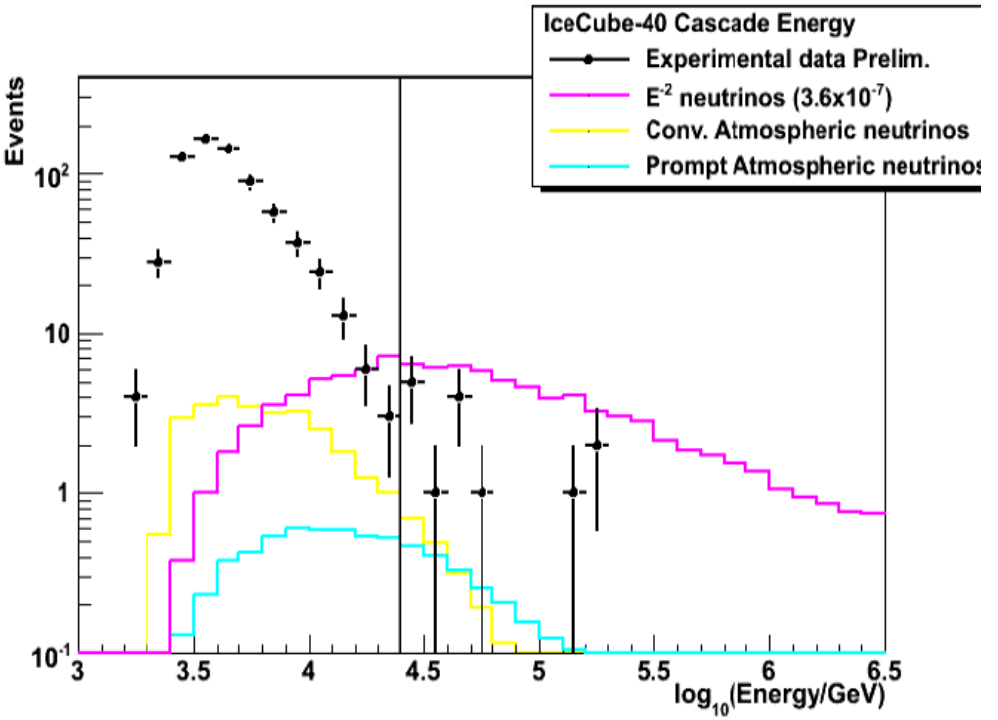
- to separate neutrinos from the by magnitudes larger atm. muon background the presented methods are typically combined in either a:
  - set of straight cuts
  - MVA method (e.g. boosted decision tree or neural net)

- additional cut on energy estimator sets the final energy threshold

- the presented IC40 analysis is tailored to search for an astrophysical E^{-2} flux above 25 TeV

2008/09 IC40 analysis by S. Hickford
ICRC'11 #0759



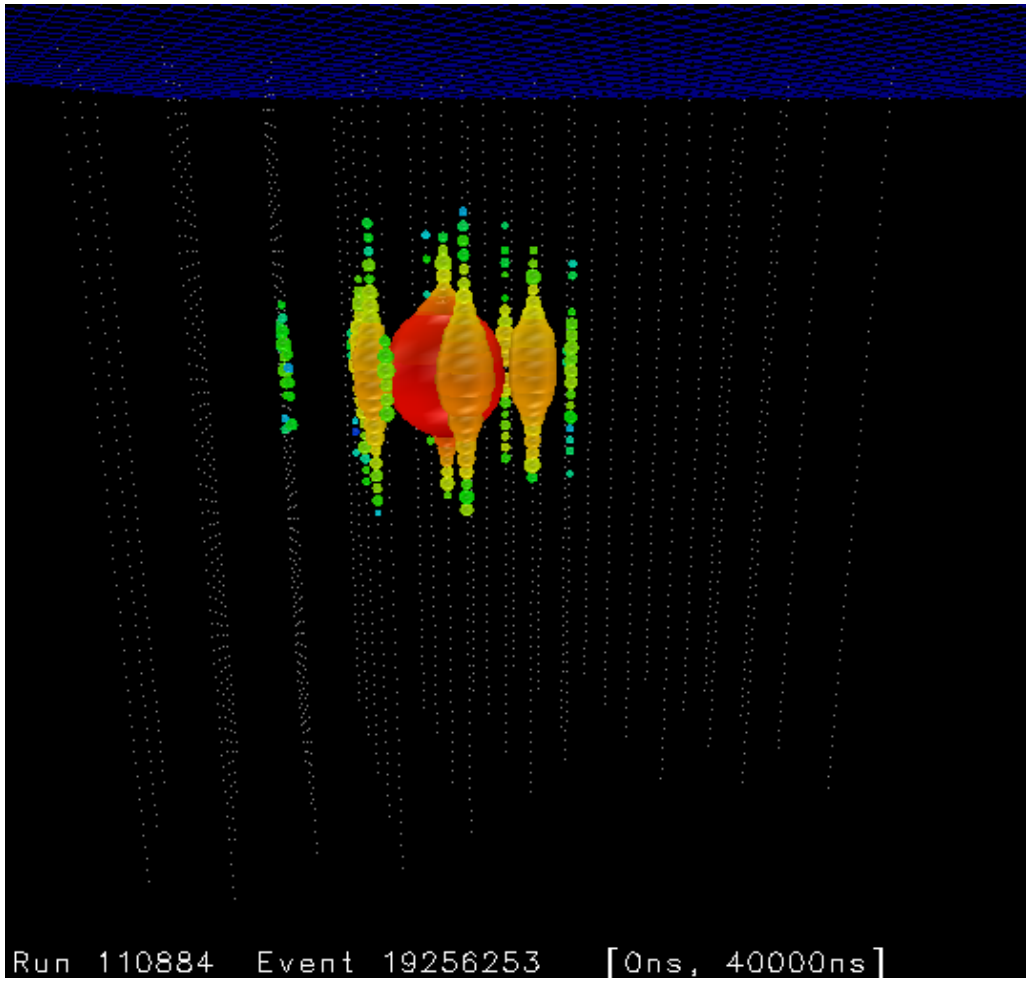


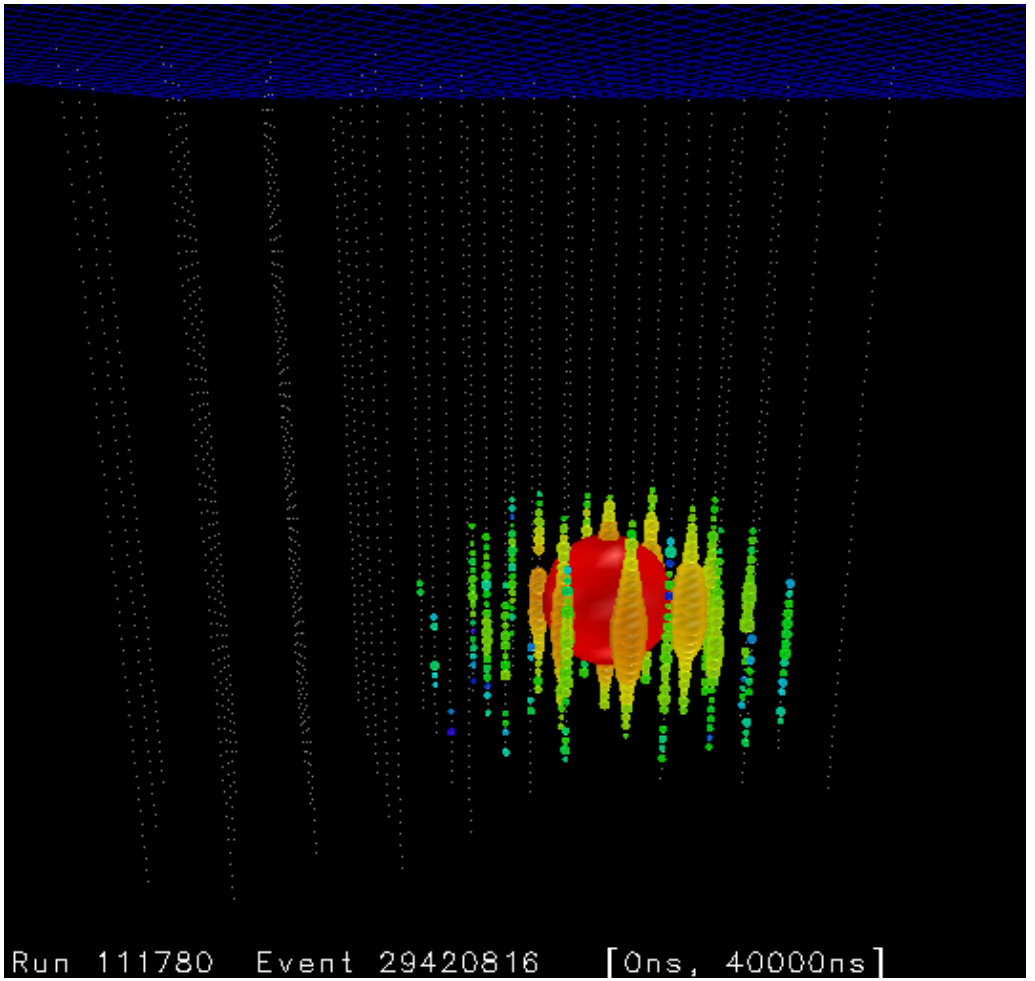
IC40 Results

- 14 events found in the 2008/2009 sample
- 3.9 events expected from atmospheric ν_e and ν_μ neutrinos (including prompt neutrinos)
- currently produce more MC statistic to provide a robust estimate of the atmospheric muon background

Run	Date	BDT response	Energy
110860	18th April 2008	0.268	29 TeV
110862	19th April 2008	0.375	31 TeV
110884	23rd April 2008	0.416	175 TeV
110964	10th May 2008	0.230	27 TeV
111076	29th May 2008	0.225	41 TeV
111113	5th June 2008	0.380	174 TeV
111281	7th July 2008	0.293	31 TeV
111558	30th August 2008	0.232	45 TeV
111780	16th October 2008	0.236	144 TeV
111917	8th November 2008	0.279	32 TeV
112406	14th January 2009	0.203	47 TeV
112782	6th February 2009	0.219	57 TeV
113693	12th May 2009	0.295	40 TeV
113802	17th May 2009	0,281	27 TeV

Example Shower Candidates





- Run 110884
- 23rd April 2008, 1:23:14
- 175 TeV

- Run 111780
- 16th October 2008, 11:32:47
- 144 TeV

Summary

- the talk presented an overview of currently used methods for shower reconstruction
- several algorithms with different computational complexity are available to separate cascade-like events from the atmospheric muon background and to reconstruct the shower parameters
- in IC40 a combination of these tools led to an event selection with 14 remaining events in the final sample
- more background MC is needed to discern the nature of these candidate events